International Journal of Electrical and
Electronics Engineering Research (IJEEER)
ISSN(P): 2250-155X; ISSN(E): 2278-943X
Vol. 6, Issue 2, Apr 2016, 1-12

DESIGN AND DEVELOPMENT OF PERMANENT MAGNET SYNCHRONOUS GENERATOR (PMSG) BASED ON SVPWM TECHNIQUES USING WIND ENERGY SYSTEM

KARTHIK SAIKUMAR

Research Scholar, Rajalakshmi Engineering College, Chennai, Tamil Nadu, India

ABSTRACT

The aim of this paper is analyze the Variable Speed Wind Turbine (VSWT) configuration is the dominant wind turbine topology available at this moment on the market. To study the performance and analysis of vector control on large wind turbines with the advance of power electronics technology for Permanent Magnet Synchronous Generator (PMSG). The Permanent Magnet Synchronous Generator (PMSG) offers better performance than other generators because of its higher efficiency and less maintenance since they don't have rotor current and can be used without gearbox, which also implies a reduction of the weight of the nacelle and reduction of costs. The Variable Speed Wind Turbine (VSWT) generator consists of another three parts: wind speed, wind turbine and drive train. The verification study demonstrated the correct implementation of FAST's furling dynamics. The whole Wind Turbine Synchronous Generator has been implemented in Matlab.

KEYWORDS: Permanent Magnet Synchronous Generator (PMSG), Variable Speed Wind Turbine (VSWT), Pulse Width Modulation (PWM)

Received: Jan 09, 2016**; Accepted:** Jan 21, 2016**; Published:** Mar 01, 2016**; Paper Id.: IJEEERAPR20161**

Original Article

INTRODUCTION

Wind turbine technology has developed rapidly over the past decade into one of the most mature renewable power generation system. Compared to other wind turbine systems used for commercial power generation, the acceleration evolution of the Direct- Drive Wind Turbine (WT) with a permanent magnet synchronous generator (D-PMSG) can be attributed to its simple structure. Low cost maintenance, high conversion efficiency and high reliability. Moreover, its decoupling control performance is much less sensitive to the parameter variations of the generator. Therefore, a high performance variable speed generation including high efficiency and high controllability is expected by using a PMSG for a wind generation system.

The third part discusses the simulation results. Aeroelasticity of wind turbines is the most important characteristic under research concerning wind turbines. The combination of aerodynamic, elastic and inertial forces acting on the wind turbine is very important in determining the efficiency and safety of wind turbines. Aeroelastic simulation is tool which helps to investigate the static and dynamic response of a wind turbine under various forces of excitation from different wind conditions. A clear understanding about the aerodynamics, structural dynamics and the interaction between these two enable the development engineers to design light weight highly efficient wind turbines. International Electro technical commission (IEC) has structured rules and standards which should be used to design and certify small and large wind turbines. IEC has also recognized Aeroelastic simulation as a tool which can be used to evaluate the forces acting on the turbine.

THE WIND TURBINE SYSTEM

Wind Energy is available and clean source of energy that has been used to generate the electrical power. The system in figure 1 analyzed is variable speed wind turbine based on a multi-pole PMSG. Due to the low generator speed, the rotor shaft is coupled directly to the generator, which means that no gearbox is needed. The generator is connected to grid via an AC/DC/AC converter, which consists of an uncontrolled diode rectifier , boost chopper circuit and SV-PWM voltage source inverter. For this topology of converter, operation at relatively low wind speeds is possible due to the inclusion of the boost circuit. A transformer is located between the inverter and the point common connection in order to raise the voltage by avoiding losses in the transport of the current. The layout of the electrical part is depicted in figure. It must be noted that this study is dedicated to analyze and implement the model from the wind turbine to the permanent magnet synchronous generator (PMSG).

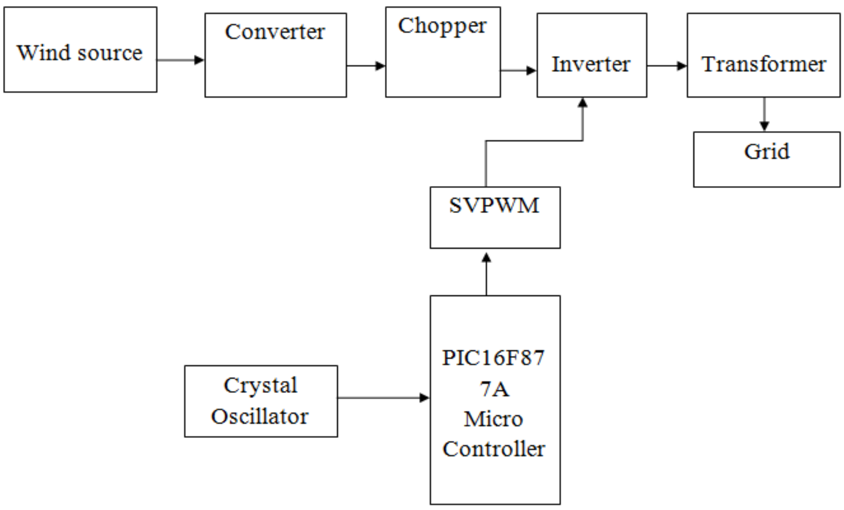

Figure 1: Block Diagram of Wind Turbine System

FAST AEROELASTIC WIND TURBINE MODEL

In general, define a aerodynamic and structural model of wind turbine given the turbine geometry and aerodynamic and mechanical properties of its members and simulate the wind turbine's aerodynamic and structural response by imposing complex, virtual, wind inflow conditions. Outputs of the simulations include time series data on the aerodynamic loads. The FAST (Fatigue, Aerodynamics, Structures and Turbulence) shown in Figure 2 is capable of predicting both the extreme and fatigue loads of two-and three-bladed horizontal axis wind turbines. It is proven that the structural model of FAST is of higher validity than other codes. During time marching analysis, the FAST makes it possible to control the turbine. At one time, FAST was an acronym for Fatigue, Aerodynamics, Structures, and Turbulence, but it is known simply as FAST today. FAST is a publicly available aeroelastic simulator for two or three-bladed HAWTs. Aeroelastic basically means it simulates the interactions of aerodynamic forces (wind) with mechanical bodies (tower, nacelle, rotor, etc).

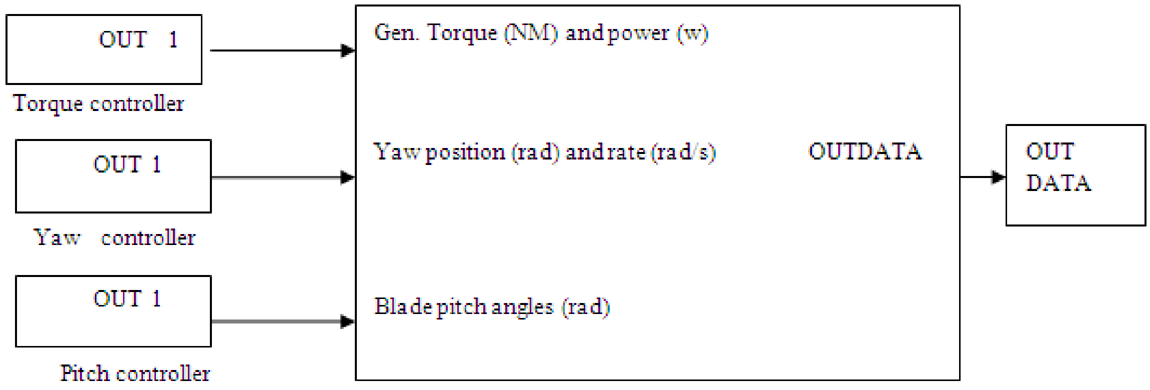

Figure 2: FAST Wind Turbine Model

Two different wind turbines were considered. Both are permanent-magnet direct- drive (PMDD) systems. The first is a 10 kW system based heavily on the Bergey Excel 10 machine. The second is a 5 MW system based on the fictional NREL 5 MW turbine. Systems of such different sizes were chosen intentionally so that the final products would be one test bed representative of small wind turbines and one representative of large turbines. Following is a short summary of the FAST models for each machine. The simulation shows in results.

Turbsim

TurbSim uses stochastic models to simulate turbulent wind. It simulates "time series of three-component wind-speed vectors at points in a two-dimensional vertical rectangular grid that is fixed in space. Figure 3 shows how this idea works with a wind turbine. TurbSim output files can be used as AeroDyn input files. AeroDyn, discussed below, is a code that is used in conjunction with an aeroelastic simulator, such as FAST, to "predict the aerodynamics of HAWT's. When used with AeroDyn, a TurbSim-generated wind file consists of many fields of wind, such as the one that are "marched through" the wind turbine in time. This means that very complicated sets of turbulent, high-resolution wind data can be generated by TurbSim and used in FAST simulations. Such data sets would be very difficult to obtain from conventional wind monitoring systems.

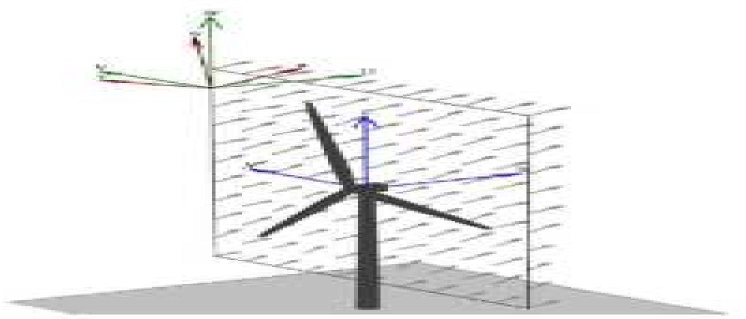

Figure 3: Turbine Wind Field Visualization

PERMANENT-MAGNET SYNCHRONOUS GENERATORS

A large amount of literature exists that details the design and operation of permanent-magnet synchronous machines (PMSMs), mostly focusing on their use as motors. But the equations are the same for motor and generator operation. The most commonly used electrical model for a PMSM is given by some form of

$$v_d = Ri_d - \rho\omega_r L_q i_q + L_d \frac{di_d}{dt} \quad \text{.........(1)}$$

$$v_q = Ri_q + \rho\omega_r (L_d i_d + \psi) + L_q \frac{di_q}{d_t} \quad \text{.........(2)}$$

$$\tau_e = \frac{3}{2}\rho(i_d i_q(L_d - L_q) + \psi i_q \quad \text{.........(3)}$$

In addition to the preceding three equations, two others that describe the mechanical dynamics of the turbine/generator are commonly used. The first mechanical equation is found in the literature as well, also with some slight variations due to sign conventions and simplifying assumptions,

$$\dot{\omega}_r = \frac{1}{J}(\tau_e - C_D\omega_r - \tau_{aero}). \quad \text{.........(4)}$$

The other mechanical equation is

$$\dot{\theta}_r = \omega_r \quad \text{.........(5)}$$

Torque and Speed Control of Permanent-Magnet Synchronous Generators

The generator-side control scheme's ultimate goal is to control the speed of the generator. Controlling generator speed allows a controller to capture as much power as possible from the wind. Figure 4. shows the generator side control scheme. Equation 7 describes the rotational dynamics of a wind turbine. The inertia and damping coefficients are obviously not controllable. (τ_{aero}), the torque on the generator shaft due to the wind, could be controlled by changing the blade pitch, but that is left for a later section. For now, assume that the blade pitch is fixed. Therefore, the term in (7) that can be used to control generator speed is τ_e, the generator torque.

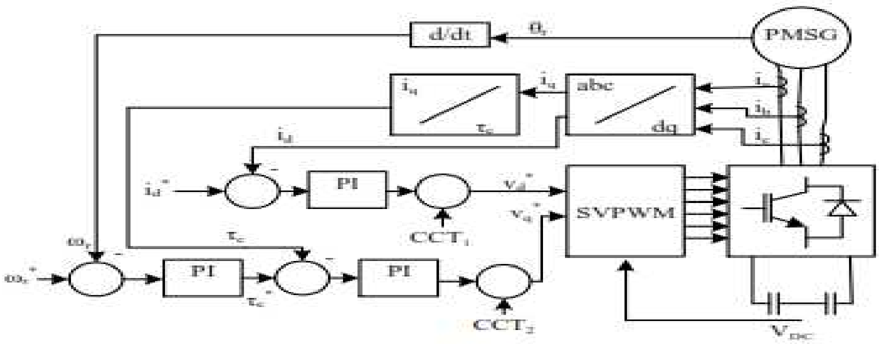

Figure 4: Generator Side Control Scheme

Torque Control

To understand how torque can be controlled, consider

$$\tau_e = \frac{3}{2}\rho\psi i_q \quad \text{.........(9)}$$

One of the conditions that a given PMSG must meet in order to work with the controllers presented here is that it must be non-salient and the above equation can be rearranged to solve for i_q and substitute with the result.

$$v_q = \frac{2R\tau_e}{3\rho\psi} + L_s\left(\frac{2}{3\rho\psi}\frac{d\tau_e}{dt} + \rho\omega_r i_d\right) + \rho\omega_r\varphi \quad \text{.........(10)}$$

Because neither ω_r nor i_d are constant, (10) is a nonlinear equation, so linear techniques cannot be used to design a controller for it. The approach that many designers of controller rectifier shave taken is to use a technique called “feedback linearization”. This technique is sometimes called “decoupling” in the literature. The basic idea of feedback linearization is to design a controller for the linear part of the system, and then add the nonlinear term(s) to the output of the controller to find the control signal. The linear part of (10), neglecting the last term, can be written in the Laplace domain as

$$v_q(s) = \frac{2}{3p\psi}\left(R\tau_e(s) + sL_s\tau_e(s)\right) \quad \text{(11)}$$

Equation (11) can then be rearranged into transfer function form as

$$\frac{\tau_e(s)}{v_q(s)} = \frac{3p\psi}{(2L_s(s)+2R)} \quad \text{(12)}$$

A parallel PI controller has the transfer function

$$G(s) = \frac{K_p\left(1+\frac{K_I}{K_p}\right)}{s} \quad \text{(13)}$$

Simulation results showing torque control for both systems.

Speed Control

As previously stated, the whole reason for controlling torque in a PMSG is so that the speed can then be controlled. Designing a speed controller is not quite as straightforward as designing a torque controller, however.

$$\dot{\omega}_r = \frac{1}{J}\left(\tau_e - C_D\omega_r - \tau_{aero}\right) \quad \text{(14)}$$

As a general rule, the more negative the real part of a PI zero, the faster the response. To further complicate matters, v_q (used to controlτ_e) is limited by the DC link voltage. It is quite possible for the control system to reach that limit by trying to change the rotor speed too quickly. This is dealt with in two ways: first, the rate at which the controller is allowed to change the rotor speed set point is limited. This is quite practical in fact because the rotor generally does not need to change its speed very quickly. The second is to employ anti-windup on the integral control. When the limit placed on the output of the integrator is reached, it saturates, the integrator is clamped at the saturation value. A PI with clamping is shown in block diagram form in Figure 5.

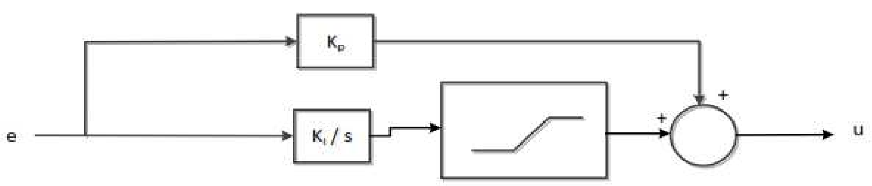

Figure 5: PI Controller with Anti-Windup

For the speed controller, e in Figure 5 is $\omega_r^* - \omega_r$ and u is τ_e^*. If the maximum rated generator torque is specified by the manufacturer, that should be the level at which the speed controller saturates. If that maximum rated torque is not known, it can be estimated based on the generator’s maximum power and voltage ratings.

FILTER AND INVERTER CONTROL DESIGN

It is most common for the DC link voltage to be controlled by the inverter, which is how the systems in this thesis operate. Therefore a control system must be designed in order to keep the DC link voltage somewhat steady at a level that is appropriate for controlling both the PMSG and the power injected into the grid. A filter must be used in order to reduce harmonic content in the inverter's output to acceptable levels and a transformer is needed to provide isolation between the inverter and the grid. A schematic for the inverter, filter, transformer, and grid is shown in Figure 6. The sensors needed for feedback signals are also shown. The first subsection of this chapter will discuss the design of LCL filter, and the second subsection will explore the design of the phase-locked loop needed for the controller. Next, expressions for active and reactive power will be formulated in the synchronous reference frame. Finally, controller design for reactive power and DC link voltage will be presented.

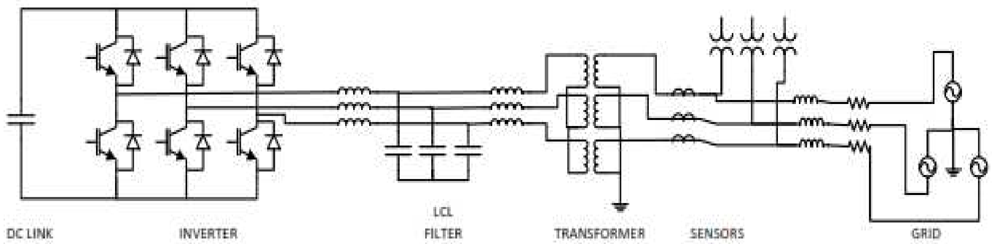

Figure 6: Schematic Diagram of Inverter, Filter, Transformer and Grid

LCL Filter Design and Transformer

It is necessary to use a filter in order to reduce the harmonics injected to the grid to acceptable levels. The simplest type of filter that can be used is a purely inductive one. However, it may take an unreasonably large inductor to provide enough filtering. Therefore, many designers have chosen to use an LCL filter such as the one shown in Figure 6. Lowpass LCL filters provide 60 dB/dec of attenuation, so they are more effective at filtering harmonics with smaller component values than lower-order filters. They have an inherent weakness, though, around their resonant frequency. Consider Figure 7 where a single phase of the filter with a resistor in series with the capacitor is shown.

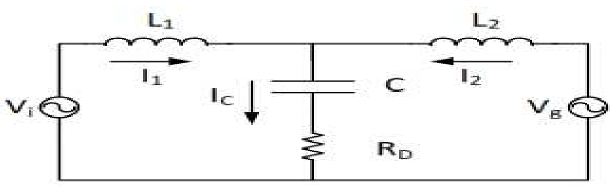

Figure 7: Single Phase of an LCL Filter with Passive Damping

The damped system has only a small "blip" around the resonant frequency. Including the damping resistor does increase the losses in the filter, which can be calculated by using

$$P_{loss} = \frac{3}{R_D} \sum_h \left[v_c(h) - v_g(h) \right]^2, \quad \text{(15)}$$

Where h is the harmonic number, v_c is the capacitor voltage, and v_g is the grid voltage. There are alternate

methods to passive damping called “active damping” that use control techniques to reduce the resonant effect. A procedure for designing LCL filters published by Lisesrre, Blaabjerg, and Hansen .The procedure is written in terms of base impedance and base capacitance, which are defined as

$$z_b = \frac{(v_g)^2}{p_n} \quad (16)$$

And

$$c_b = \frac{1}{\omega_n z_b} \quad (17)$$

Reactive Power Control

Because is set by the grid), Q can be independently controlled by controlling i_d . This gives the inverter the ability to act as a STATCOM and support the grid voltage by sourcing or sinking VARs. A feedback- linearized PI controller can be designed to control i_d . The references for this practice and for DC link voltage control may interchange the uses of i_d and i_q , because of differences in reference frame orientation. The transfer function form is

$$\frac{i_d}{v_{sd}} = \frac{1}{sL+R} \quad (18)$$

The grid definitely has some inductance and resistance from the inverter’s point of view, but it is very difficult to estimate what they may be. Therefore, the L and R used to design the controller are the total series inductance and series resistance of the filter and the primary of the transformer.

DC Link Voltage Control

The previous section explained how i_d is used to control the reactive power output of the inverter. In Dc link voltage control i_q is used to control the inverter’s active power output. It is true, i_q is used to control p ,but not directly Instead, it is common practice to use i_q to regulate the DC link voltage. This is intuitive because if the DC link voltage stays constant, all of the energy output of the active rectifier must then be transferred to the inverter, less losses of course. A general transfer function that exhibits such a curve is

$$\frac{Y(s)}{U(s)} = \frac{Ae^{-st_d}}{\tau_s+1} \quad (19)$$

Zeigler and Nichols provided guidelines from which to start the iterative tuning process based on a good tradeoff between fast response and good stability margins for the system given by (19). For a PI controller, those guidelines are

$$K_p = -\frac{0.9}{RL} \quad (20)$$

SIMULATION RESULTS

The Bergey’s power curve was found through actual test data collected in. The model’s power curve was found by setting the wind to a constant value, and then stepping through successive speed set points until the maximum steady-state electrical power was found. Figure 8 shows the wind input used for simulation results. It has been documented that the FAST model turbine spins too fast at and above 10 m/s due to the lack of blade tip torsion in FAST. Electromechanical

simulations were performed to show the high level of detail included in the models in this work, as well as the broad range of variables they are capable of simulating. Figure 9 shows the speed and torque of the generation. The generator torque is arbitrarily controlled to demonstrate the validity of the controller. As expected, the torque approximately follows the wind as the torque controller works to maintain the proper speed. The speed matches its set point well throughout the simulation. Figure 10. graphical representation shows the variation of mechanical power with respect to turbine speed. Figure 11. graphical representation shows the real power and reactive power comparison for PMSG.

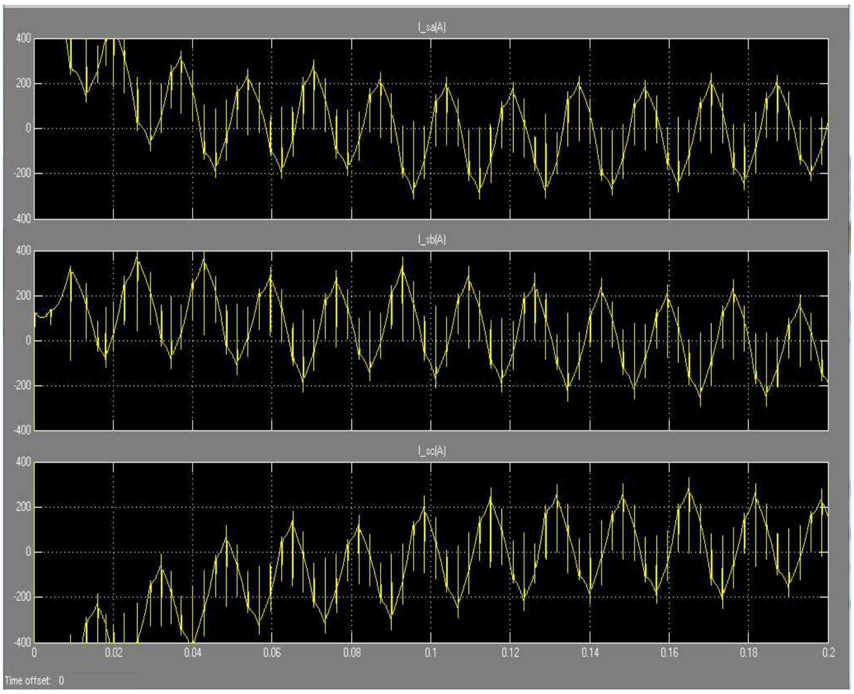

Figure 8: Wind Input Used in 100MW System Simulation

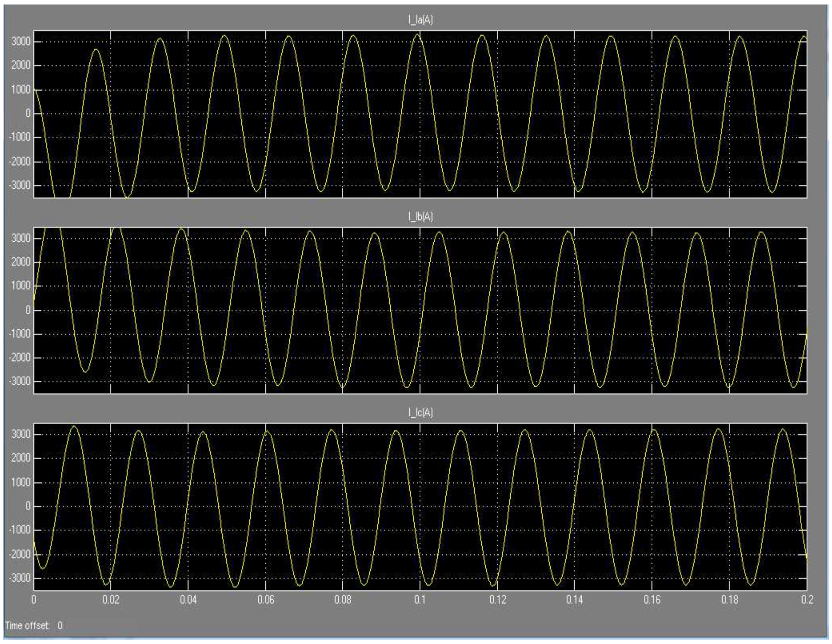

Figure 9: Generator Speed and Torque for 100MW System Simulation

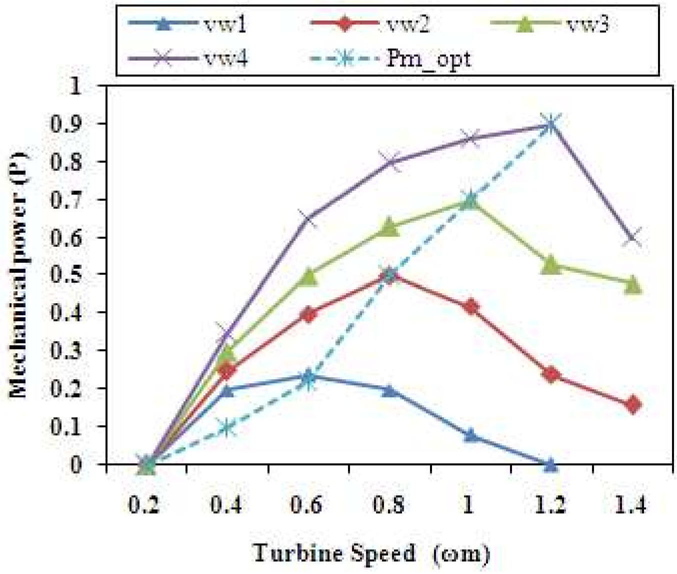

Figure 10: Variation of Mechanical Power with Turbine Speed

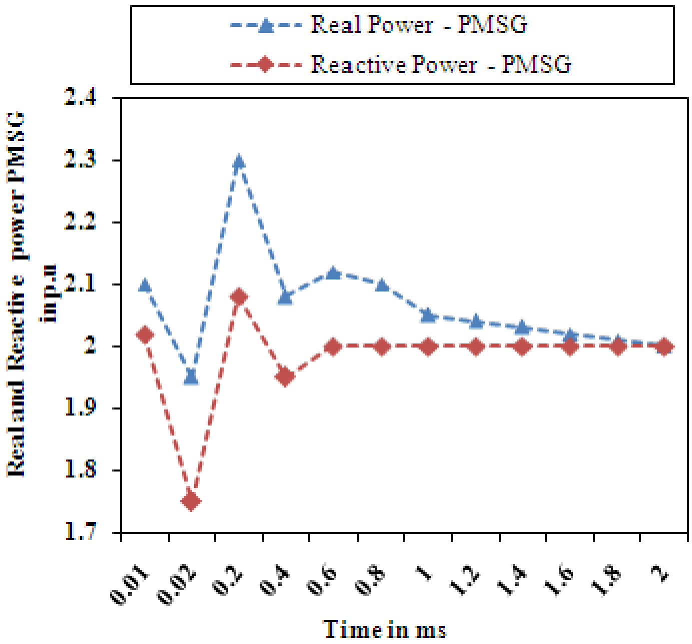

Figure 11: Real Power and Reactive Power Comparison for PMSG

CONCLUSIONS

The main objective of this paper the Variable Speed Wind Turbine (VSWT) configuration and simulation of the ultra large wind turbine system using validated models of wind turbine mechanical and electrical systems. Our manuscripts have developed in the formulation of comprehensive models of PMDD wind turbines. The models include aerodynamic, mechanical, and electrical simulations through a combination of the FAST aeroelastic simulator and the SimPowerSystems toolbox for MATLAB/Simulink. The simulation results have shown the correct functioning of the controllers applied on each component in the whole system. It also shows the high levels of the models are capable of producing.

REFERENCES

1. *H. Polinder, F.F.A. van der Pijl, G.J. de Vilder, P. Tavner, "Comparison of direct-drive and geared generator concepts for wind turbines", IEEE Trans. Energy Conversion, Vol. 21, pp. 725-733, September 2006.*
2. *D. Bang, H. Polinder, G. Shrestha, and J.A. Ferreira, "Review ofs generator systems for direct-drive wind turbines", in Proc. EWEC (European Wind Energy Conference & Exhibition,) Brussels, Belgium, March 31 - April 3, 2008.*
3. *J. Jonkman, B.J. "Turbsim user's guide". s.l. : NREL/TP-500-46198: National Renewable Energy Laboratory., August 2009.*
4. *J. Jonkman, S. Butterfield, W. Musial, and G. Scott. "Definition of a 5MW Reference Wind Turbine for Offshore System Development". s.l. : NREL, February 2009.*
5. *Cristian Busca, Ana-Irina Stan, Tiberiu Stanciu and Daniel Ioan Stroe."Control of Permanent Magnet Synchronous of large wind turbines". Denmark : Departament of Energy Technology: Aalborg University, November 2010, Industrial Electronics (ISIE), ieee, pp. 3871 - 3876 .*
6. *D. Bang, H. Polinder, J.A. Ferreira. "Design of Transverse Flux Permanent Magnet Machines for Large Direct-Drive Wind Turbines". Electrical Power Processing / DUWIND, Delft University of Technology.*
7. *Hui Li, Zhe Chen. "Design Optimization and Evaluation of Different Wind Generator Systems".February 2009, Sustainable Power Generation and Supply, 2009. SUPERGEN '09.*
8. *Li, Hui, Chen, Zhe and Polinder, H. "Optimization of multibrid permanent-magnet wind generator systems". Security & New Technol., Chongqing Univ : IEEE Transactions on Energy conversion, March 2009, IEEE Transactions on Energy conversion , Vol. 24, pp. 82-92.*
9. *Floren lov, FredeBlaabjerg. "Power electronics Control of wind energy in distributed power systems". Department of energy technology, Aaloborg university. 2009. pp. 1–16.*
10. *Shuhui Li, Timothy A.Haskew, Ling Xu. "Conventional and novel control designs for direct driven PMSG wind turbines". 3, March 2010, Electric Power Systems Research, Vol. 80, pp. 328-338.*
11. *Remus Teodorescu, Pedro Rodriguez. "Thesis in Reactive power control for wind power plant with STATCOM". Institute of Energy Technology Pontoppidanstræde 101. 2010.Master thesis.*
12. *Busca, C., et al., et al. "Vector control of PMSG for wind turbine applications". s.l. : Dept. of Energy Technol., Aalborg Univ., Aalborg, Denmark , 2010 , Industrial Electronics (ISIE), pp. 3871 - 3876 .*
13. *Andreea Cimpoeru, Kaiyuan Lu. "Encoderless Vector Control of PMSG for wind turbine applications". Institute of Energy Technology, Institute of energy technology. s.l.: AALBORG University, 2010.*
14. *Michael J. Grimble, Professor Michael A. Johnson. "Optimal Control of Wind Energy Conversion Systems". August 2007 .*
15. *E. Mahersi, A. Khedher, M. F. Mimouni, "The Wind energy Conversion System Using PMSG Controlled by Vector Control and SMC Strategies,"published in international journal of renewable energy research Vol.3, No.1, 2013 vol. 3, no. 1, 2013.*
16. *Natalia Angela Orlando, Marco Liserre, , Rosa Anna Mastromauro, M and Antonio Dell'Aquila. "A Survey of Control Issues in PMSG-Based Small Wind-Turbine Systems. Proceedings of IEEE transactions on industrial.*
17. *D. Ahmed and a Ahmad, "An optimal design of coreless direct -drive axial flux permanent magnet generator for wind turbine," J. Phys. Conf. Ser., vol. 439, p. 012039, Jun. 2013.*
18. *B. Plangklang, S. Kantawong, and A. Noppakant, "Study of Generator Mode on Permanent Magnet Synchronous Motor (PMSM) for Application on Elevator Energy Regenerative Unit (EERU)," Energy Procedia, vol. 34, pp. 38 2–389, Jan. 2013.*

19. *Y. Xia, K. Ahmed, and B. Williams, "Wind turbine power coefficient analysis of a new maximum power point tracking technique," IEEE transition on industrial Electronics. vol. 60, no. 3, pp. 1122–1132, 2013.*
20. *G. Revel, A. Leon, D. Alonso, and J. Moiola, "Dynamics and Stability Analysis of a Power System With a PMSG-Based Wind Farm Performing Ancillary Services," IEEE transaction on , pp. 1–12, 2014.*
21. *S. Alshibani at el," Lifetime Cost Assessment of Permanent Magnet Synchronous Generators for MW Level Wind Turbines ,",IE transition on industrial electronic. vol. 5, no. 1, pp. 10–17, 2014.*
22. *D. Ochs, R. Miller, and W. White, "Simulation of Electromechanical Interactions of Permanent -Magnet Direct-Drive Wind Turbines Using the FAST Aeroelastic Simulator," pp. 1–8, 2014.*
23. *OLIMPO ANAYA-LARA, NICK JENKINS "Wind Energy Modulation and Control" John Wiley & Sons, Ltd 2009.*
24. *MUKUND R PATEL "Wind and Solar Power System" CRC Press 2011Edition.*
25. *JOSHUA EARNEST & TORE WILZELIUS "Wind Power Plant and Projects Development" PHI learning 2012Edition.*